NEAR-EARTH ASTEROID LIGHTCURVE ANALYSIS AT THE CENTER FOR SOLAR SYSTEM STUDIES: 2021 JANUARY - MARCH

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Lightcurves of 20 Near-Earth asteroids (NEAs) obtained at the Center for Solar System Studies (CS3) from 2021 January through March were analyzed for rotation period, peak-to-peak amplitude, and signs of satellites or tumbling.

CCD photometric observations of 20 near-Earth asteroids (NEAs) were made at the Center for Solar System Studies (CS3) from 2021 January through March. Table I lists the telescopes and CCD cameras that were combined to make observations.

Up to nine telescopes can be used for the campaign, although seven is more common. All the cameras use CCD chips from the KAF blue-enhanced family and so have essentially the same response. The pixel scales ranged from 1.24-1.60 arcsec/pixel.

Telescopes	Cameras
0.30-m *f*/6.3 Schmidt-Cass	FLI Microline 1001E
0.35-m *f*/9.1 Schmidt-Cass	FLI Proline 1001E
0.40-m *f*/10 Schmidt-Cass	SBIG STL-1001E
0.40-m *f*/10 Schmidt-Cass	
0.50-m *f*/8.1 Ritchey-Chrétien	

Table I. List of available telescopes and CCD cameras at CS3. The exact combination for each telescope/camera pair can vary due to maintenance or specific needs.

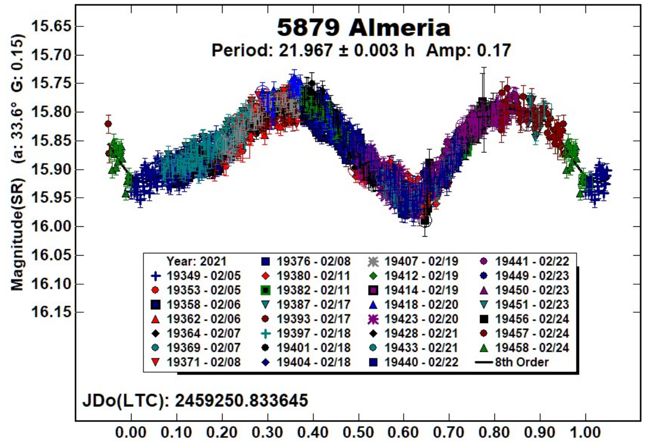
All lightcurve observations were unfiltered since a clear filter can cause a 0.1-0.3 mag loss. The exposure duration varied depending on the asteroid's brightness and sky motion. Guiding on a field star sometimes resulted in a trailed image for the asteroid.

Measurements were made using *MPO Canopus*. The Comp Star Selector utility in *MPO Canopus* found up to five comparison stars of near solar-color for differential photometry. To reduce the number of times and amounts of adjusting nightly zero points, we use the ATLAS catalog r´ (SR) magnitudes (Tonry et al., 2018). Those adjustments are usually $|\Delta| \leq 0.03$ mag. The larger corrections, which are rare, may have been related in part to using unfiltered observations, poor centroiding of the reference stars, and not correcting for second-order extinction. Another cause may be selecting what appears to be a single star but is actually an unresolved pair.

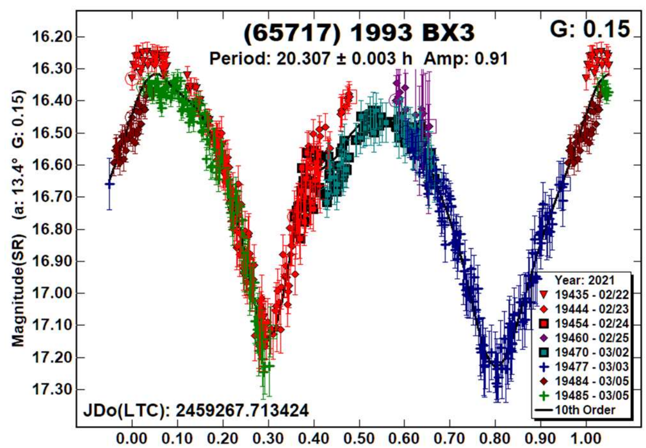
The Y-axis values are ATLAS SR "sky" (catalog) magnitudes. The two values in the parentheses are the phase angle (a) and the value of *G* used to normalize the data to the comparison stars used in the earliest session. This, in effect, had all the observations made at a single fixed date/time and phase angle, leaving any variations due only to the asteroid's rotation and/or albedo changes. The X-axis shows rotational phase from –0.05 to 1.05. If the plot includes the amplitude, e.g., "Amp: 0.65", this is the amplitude of the Fourier model curve and *not necessarily the adopted amplitude for the lightcurve*.

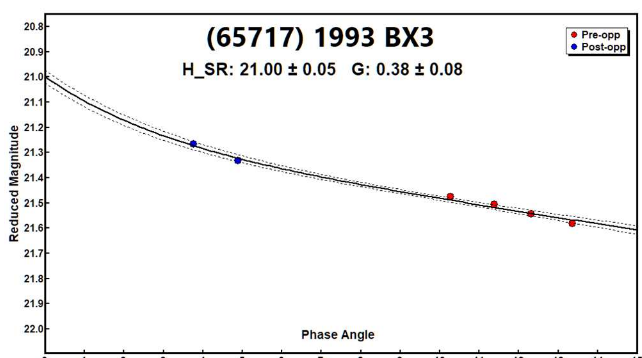
"LCDB" refers to Warner et al. (2009) from here on.

5879 Almeria. Warner (2017) found a period of 13.67 h based on a noisy sparse data set from 2017. Our 2021 data set (1,500 data points over 19 days) led to P = 21.967 h. The period spectrum using the 2021 data confirms an essentially zero chance for 13.7 h.

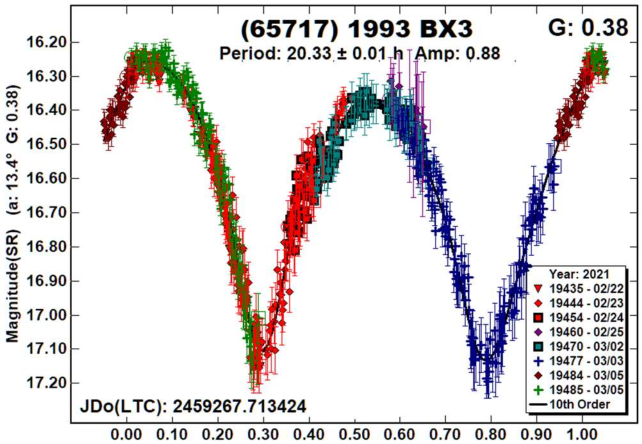


(65717) 1993 BX3. Mottola et al. (1995) found a period of 20.463 h for this 200-m NEA. Pravec et al. (2020web) reported 20.294 h. Our result is in good agreement with those earlier reports.

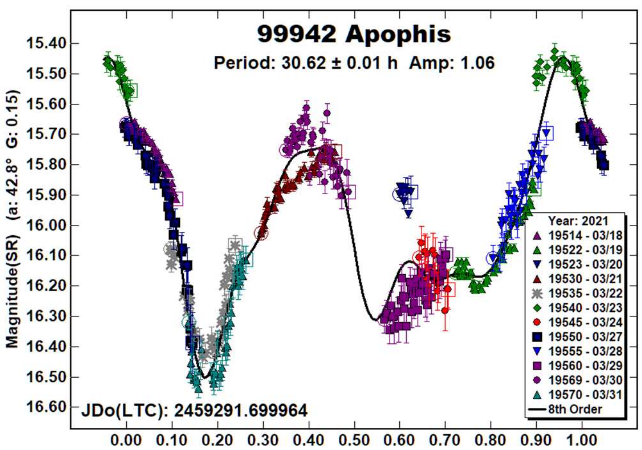




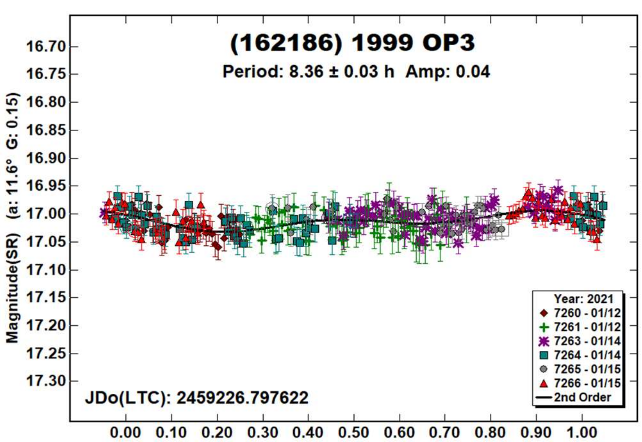
During period analysis, we found using the default of G = 0.15 produced an ill-fitting lightcurve. Our data covered a sufficient range of phase angles to find a new value of G_{SR} = 0.38. When this value was used, almost no or very small zero-point adjustments were required to produce a clean-fitting lightcurve. Assuming V-SR = 0.22 (Warner and Stephens, 2021), gives H = 21.22. The MPCORB catalog gives H = 20.7.



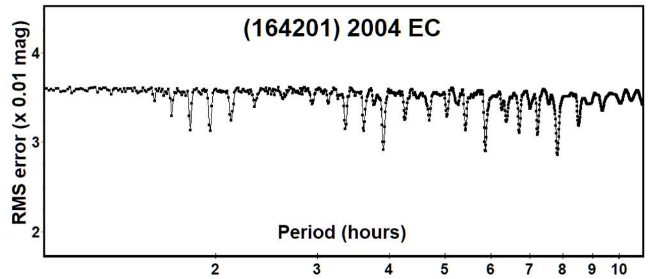
99942 Apophis. The tumbling state of Apophis was well-studied by Pravec et al. (2014). They found the strongest lightcurve amplitude was in the second harmonic of $P_1 = (P\phi^{-1} - P\psi^{-1})^{-1} = 30.56$ h. The true periods for precession and rotation are $P\phi = 27.38$ h and $P\psi = 263$ h. Our data clearly show that the asteroid is tumbling and that our result of the dominant period found by *MPO Canopus* closely matches Pravec et al. (2014).

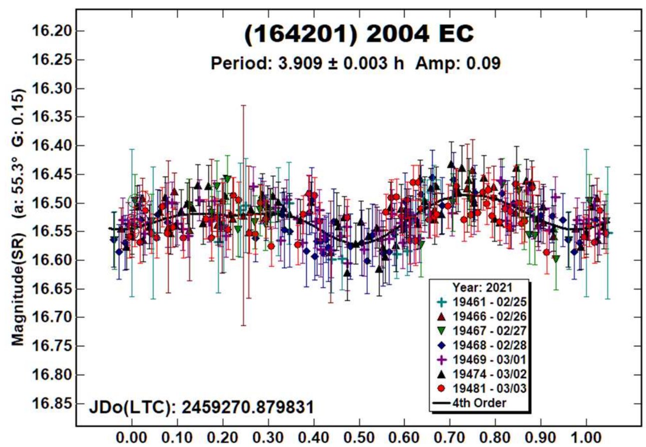


(162186) 1999 OP3. With such a flat lightcurve, our result could be the result of the Fourier analysis latching onto noise and so the period of 8.36 h is highly questionable.

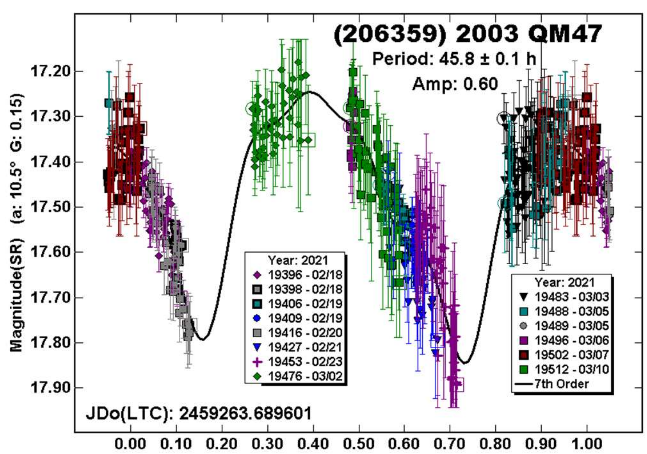


(164201) 2004 EC. Galad and Kornos (2008) found a period of 6.642 h. The period spectrum based on our data shows a weak solution near that result as well as several strong possibilities. We adopted $P = 3.909$ h, which produced a bimodal lightcurve. With such a low amplitude, a mono- or multimodal lightcurve is possible as well (Harris et al., 2014). The asymmetry of the bimodal lightcurve proved helpful in rejecting those other solutions.



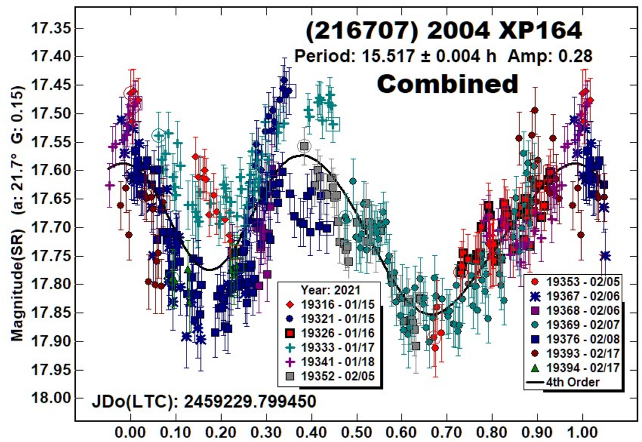


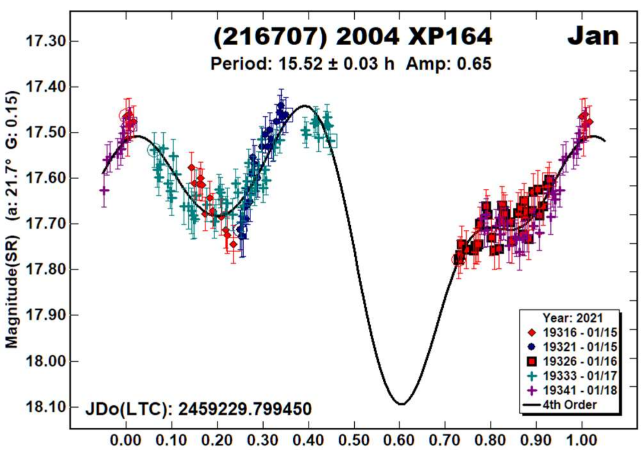
(206359) 2003 QM47. There were no previous results in the LCDB for this 750-m NEA. Despite the noisy data, we were able to find a reasonably reliable period of 45.8 h. We also tried other periods that were nearly commensurate with an Earth day. The resulting lightcurves were considered implausible.

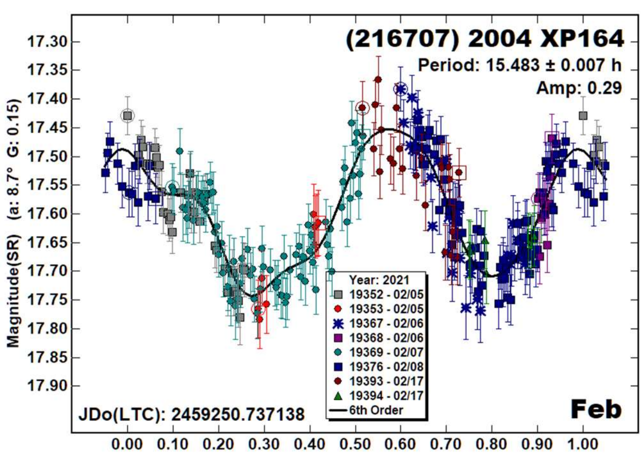


(216707) 2004 XP164. We observed this 950-m NEA for two nights. The combined lightcurve, with a single period solution, shows good overlap from the two nights in some places but considerable difference in others. Given the size and dominant period of 15.5 h, tumbling is possible, bordering on likely (Pravec et al., 2005; 2014). However, also possible is that the shape of the lightcurve changed dramatically as the phase angle decreased from 21° to 9°. Splitting the data into individual nights shows a good fit to a single period for the February data (15.483 h). The January data set gave P = 15.52 h but wasn't able to cover a full lightcurve.

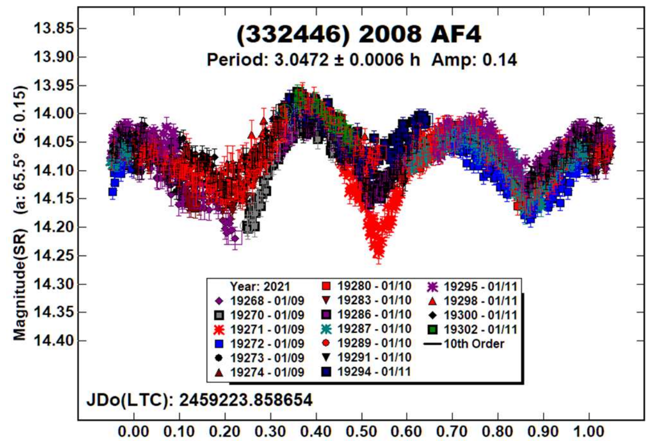
Whether or not the asteroid is in a tumbling state cannot be confirmed from our data set alone. Unfortunately, the next time 2004 XP164 is V < 18 is not until 2037 January, when it will be V ~ 17.2 at a Declination of -6°.

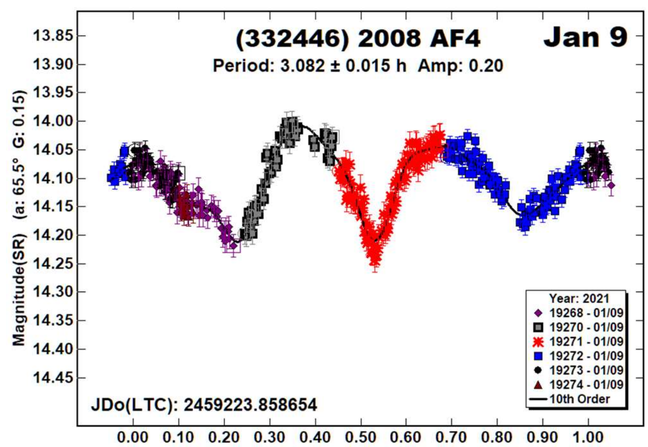


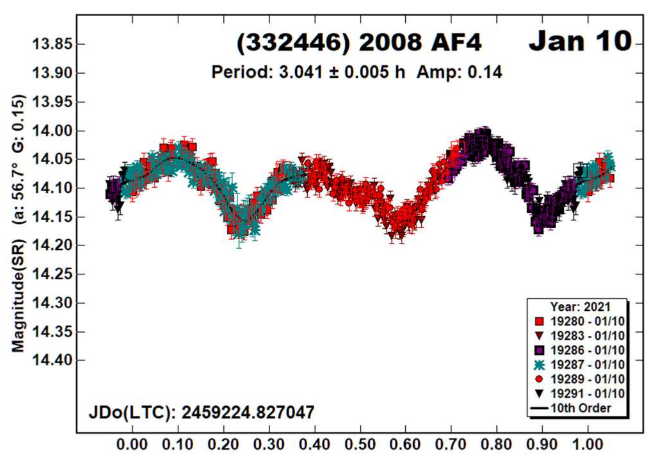


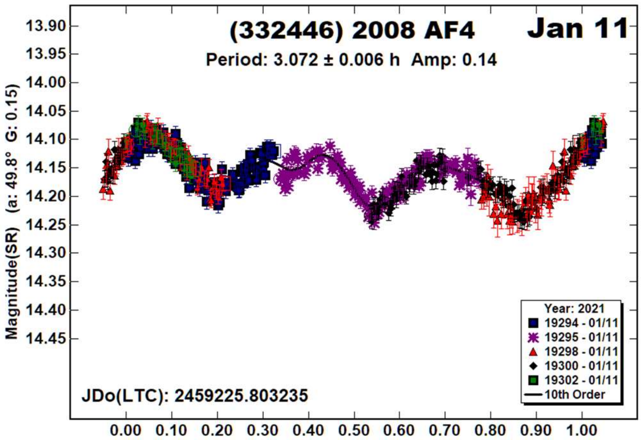


(332446) 2008 AF4. The shape of the lightcurve for this 350-m NEA also changed dramatically over the range of our observations. This is clearly shown when trying to plot the full data set to a single period. The large phase angles probably allowed shadowing effects to influence the lightcurve shape, being trimodal in the combined and Jan 9-10 plots but almost quadrimodal for Jan 11.



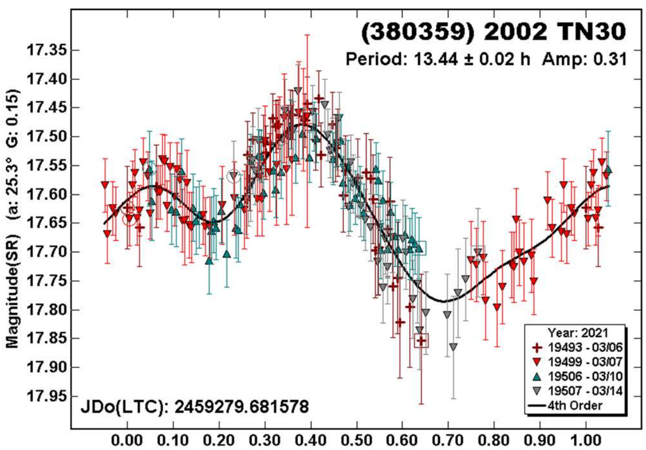




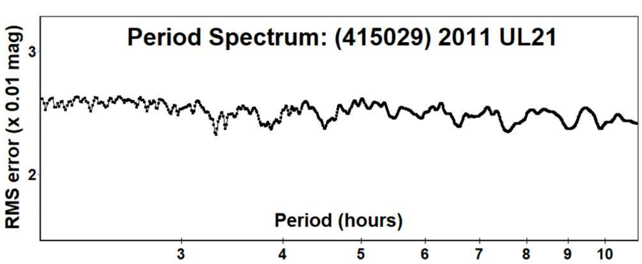


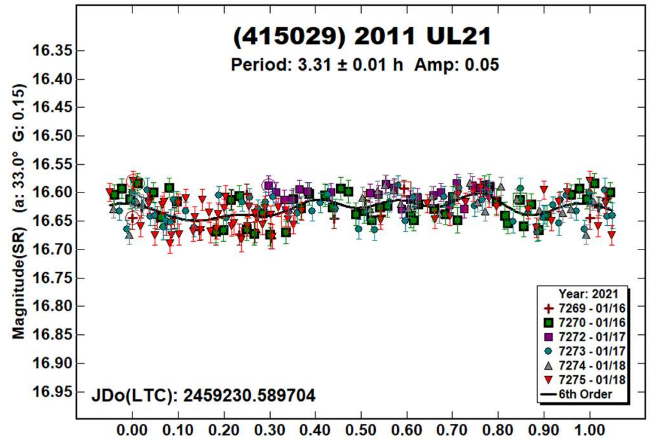
Splitting the data set into separate nights shows that the sidereal period decreased as the phase angle decreased. This is usually interpreted to mean that the asteroid rotation is prograde.

(380359) 2002 TN30. The estimated diameter for 2002 TN30 is 1 km. There were no previous entries in the LCDB. While the lightcurve shape is asymmetrical, no other period produced a plausible lightcurve.



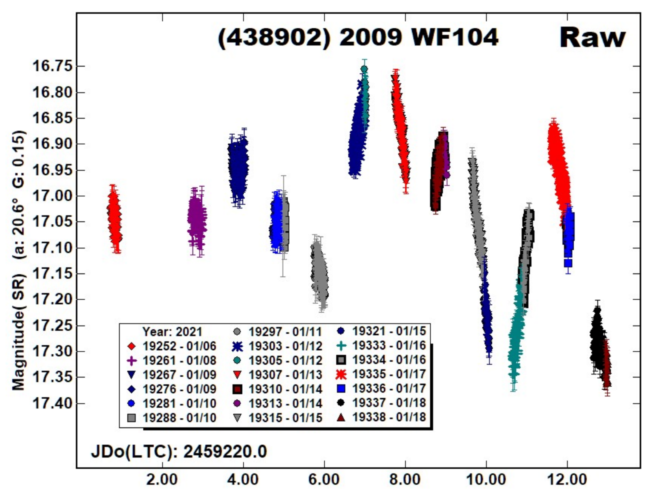
(415029) 2011 UL21. Warner (2018a) found an unreliable (U = 1) period of 1.562 h in 2017. The amplitude at that time was very low. However, observations six months later (Warner, 2018b) revealed a lightcurve with 0.32 mag amplitude and reliable period of 2.732 h. The 2021 data also produced an unreliable solution because of low amplitude. It's worth noting that the 3.31 and 2.732 h periods have a very close to 6:5 ratio.

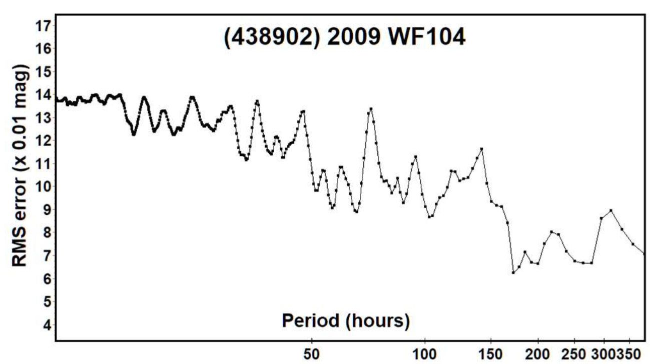


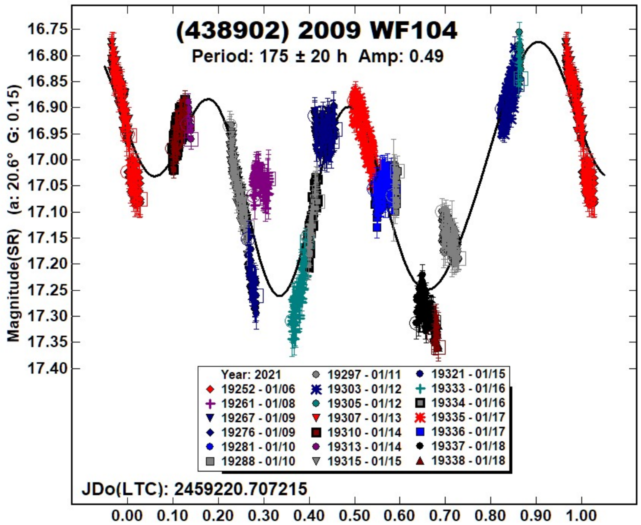


(438902) 2009 WF104. There were no previously reported rotation periods in the LCDB. Using the default albedo of 0.2 and the MPCORB H = 17.3 gives a diameter of 1.03 km. However, Mainzer et al. (2019) using WISE data and H = 17.2 found D = 2.23 km. This leads to a derived albedo of 0.047, which is notably darker than the typical NEA with a taxonomic class in the S complex. Such presumed interlopers are not unexpected.

The raw plot of the data shows seemingly good evidence that the asteroid is tumbling. This highly likely based on the derived period and diameter (Pravec et al., 2005; 2014). *MPO Canopus* could find only the dominant period, which is possibly the second-order harmonic of the rotation and precession frequencies (see the discussion for 99942 Apophis above).

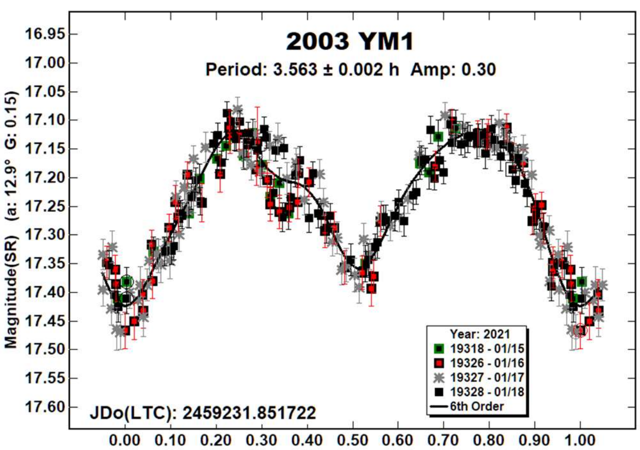




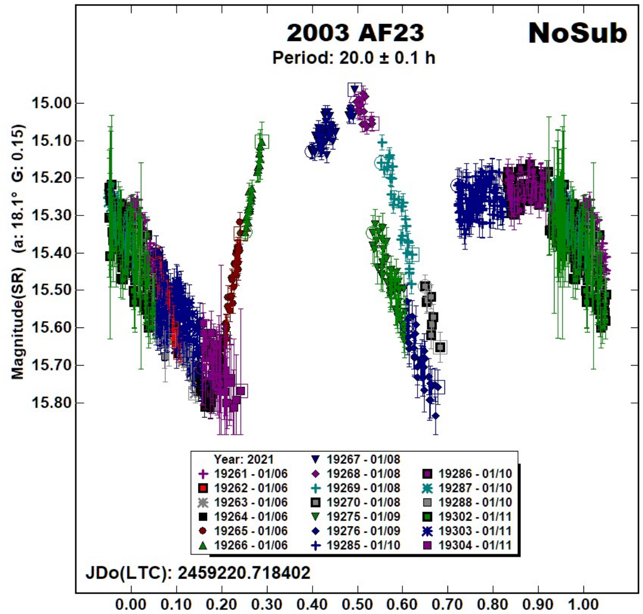


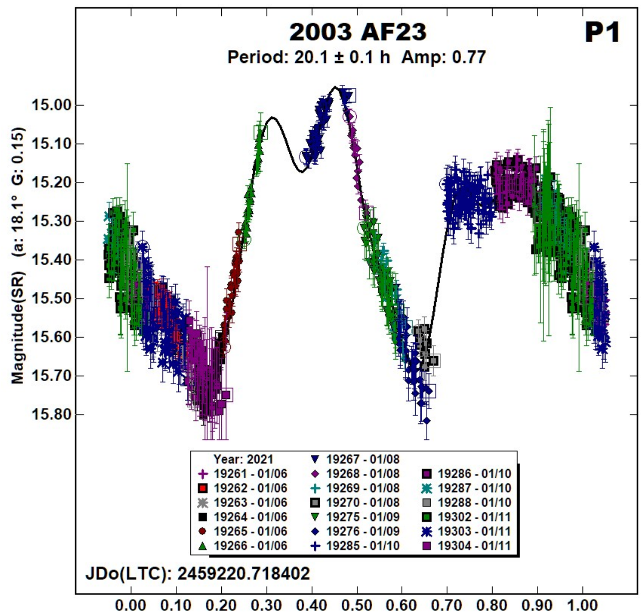
A follow-up campaign involving several observers is unlikely: the asteroid remains V < 19.5 through 2050.

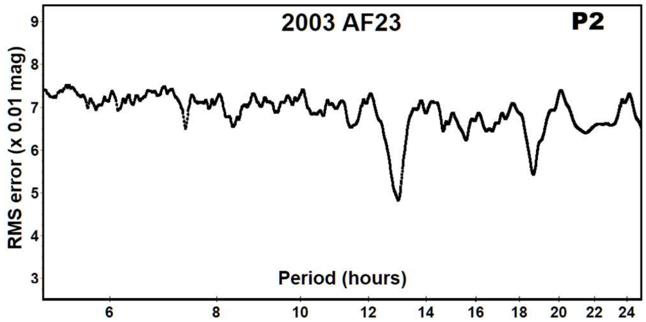
<u>2003 YM1</u>. The estimated diameter for 2003 YM1 is 750 m. There were no previously reported periods in the LCDB.

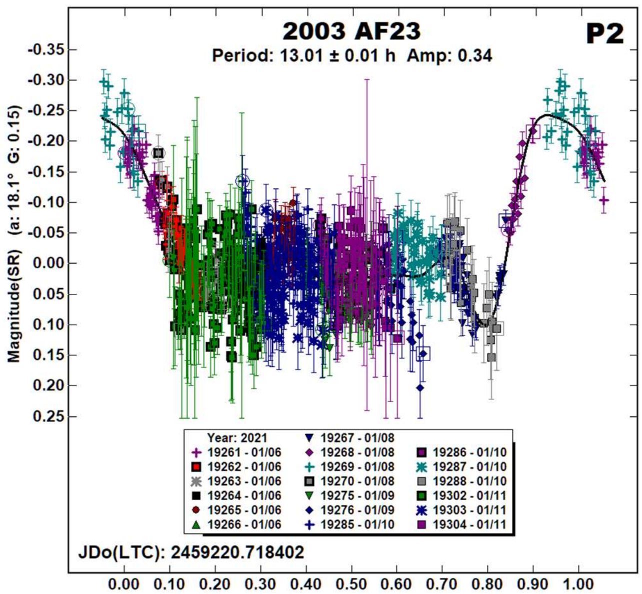


<u>2003 AF23</u>. There were no previous entries in the LCDB for this 180-m asteroid. It’s size and the dominant period near 20 h make this a likely tumbling asteroid candidate (Pravec et al., 2014; 2005).



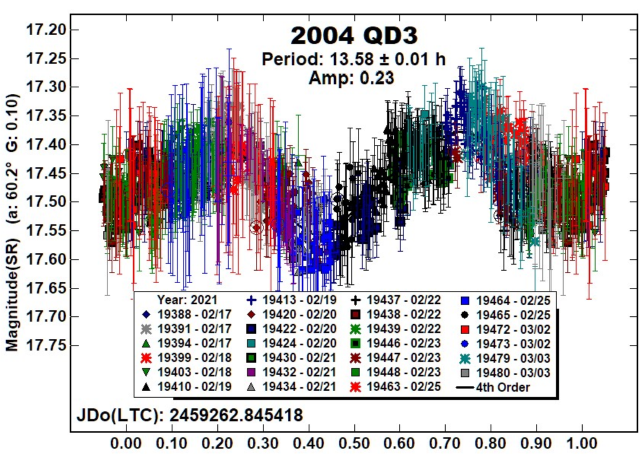


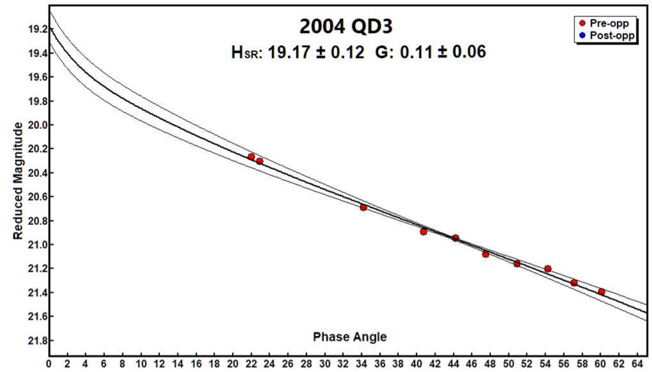




The "NoSub" plot shows that a single period solution was not going to be possible. We tried the dual-period search in *MPO Canopus* despite it not being able to handle tumbling asteroids properly. This led to a dominant period of 20.1 h but even so, the fit of the data to the model curve is marginal. The lightcurve for the second period of 13.01 h seems physically improbable, leaving it and the dominant period to be harmonics of the true periods of precession and rotation, or some unexplained systematic problem.

<u>2004 QD3</u>. Despite the noisy data set we were able to find a secure a result of 13.58 h for this 400-m NEA. The observations covered a sufficient range of phase angles to allow finding the H-G parameters.

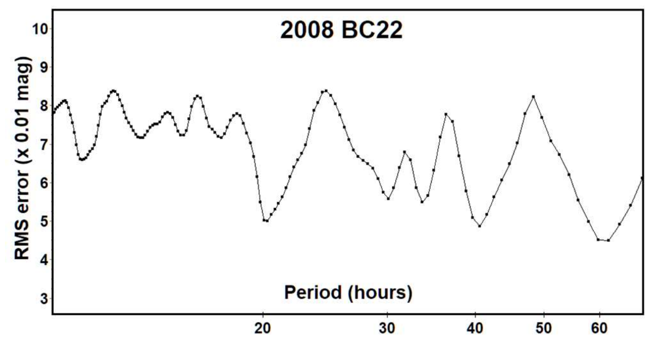


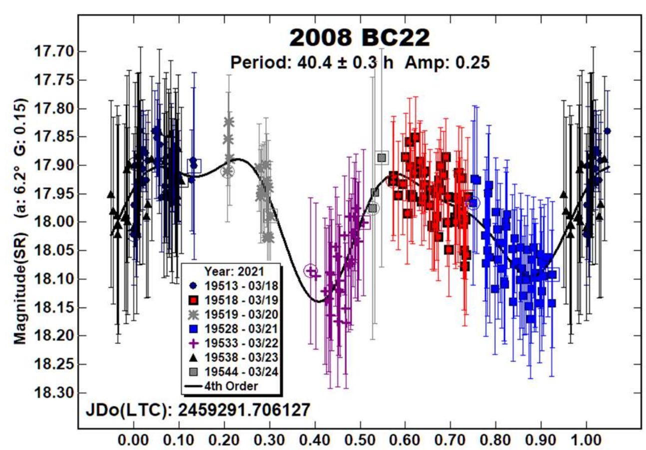


Assuming V-SR = 0.22 (Warner and Stephens, 2021) gives $H = 19.39$. This is very close to the MPCORB $H = 19.4$.

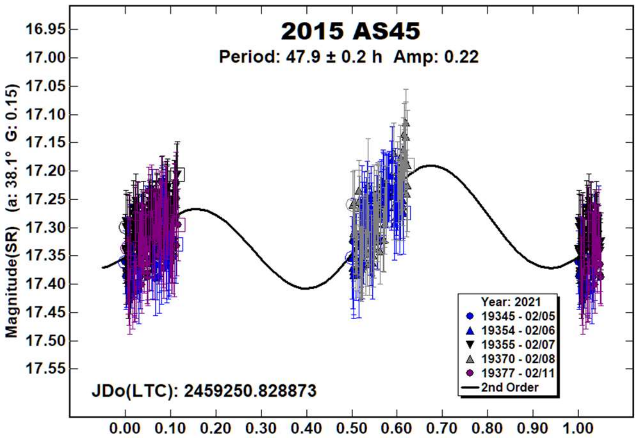
The value for G is on the lower end of those allowed for S-type asteroids. However, it's also well within the range of those for C-type asteroids (Warner et al, 2009). Barring spectroscopic or multi-color observations, the taxonomic class is uncertain. Since the average albedos for the two classes differ by 0.16, the actual diameter could range from 400 m (type S) to 700 m (type C) when using $H = 19.4$.

<u>2008 BC22</u>. The noisy and sparse data set for 2008 BC22, with an estimated diameter of 400 m, could produce only a marginally useful solution. Given the low phase angle and almost 0.3 mag amplitude, we opted for a bimodal lightcurve solution (Harris et al., 2014).

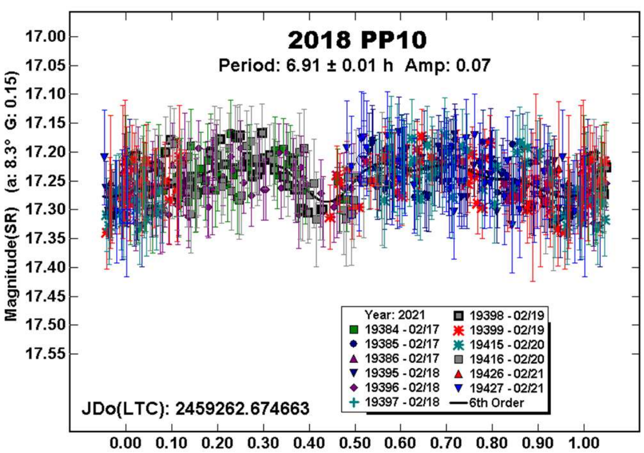




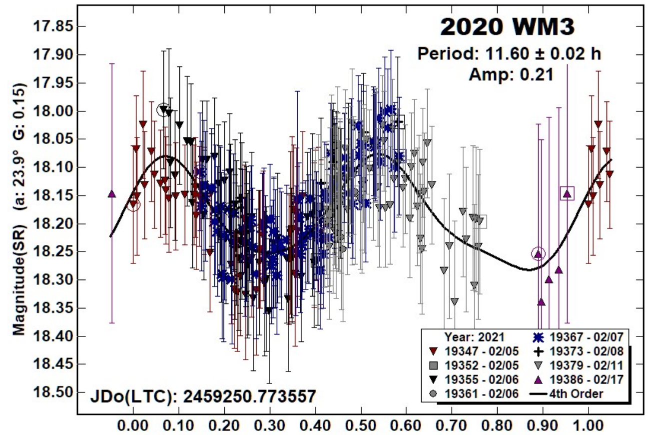
2015 AS45. Several Earth-day commensurate solutions were in the period spectrum. The lightcurve at 47.9 h is bimodal but a monomodal solution at 24 h is also possible. In that case, the amplitude would be significantly larger. The half-period (near 12 h) lightcurve was too shallow compared to the slopes of the raw data from individual nights.



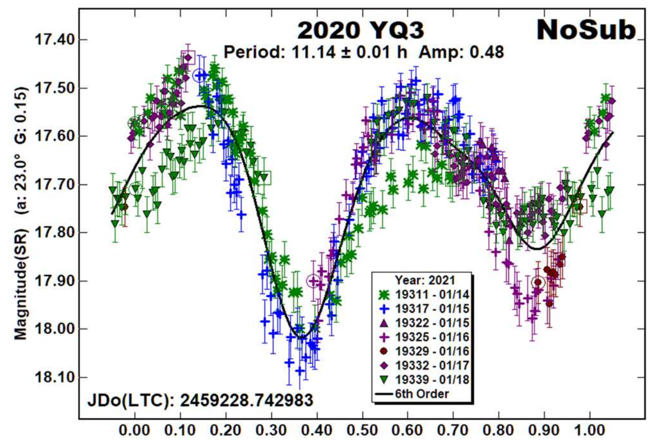
2018 PP10. Noise and low amplitude contributed to finding an uncertain solution of 6.91 h. The period spectrum showed some other, harmonically related, periods but we chose the period that gave the most probable lightcurve.



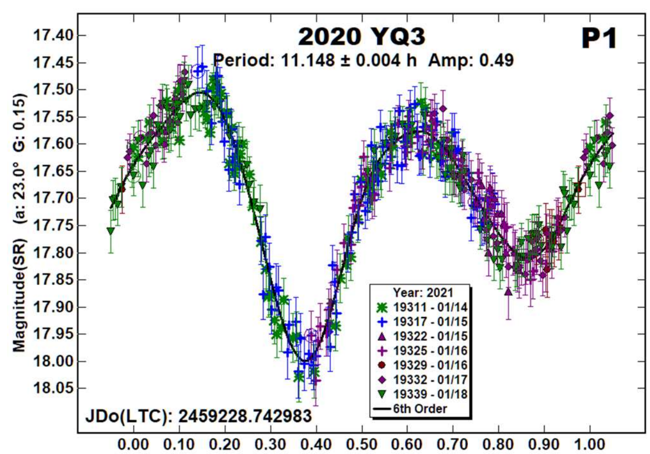
2020 WM3. There were no rotation periods found in the LCDB for the 500-m 2020 WM3. This is another asteroid with a period nearly commensurate with an Earth day. The slopes of the Fourier curve at 11.60 h were similar to those for the data on individual nights. However, the half-period at 5.8 h with a monomodal lightcurve cannot be formally excluded.

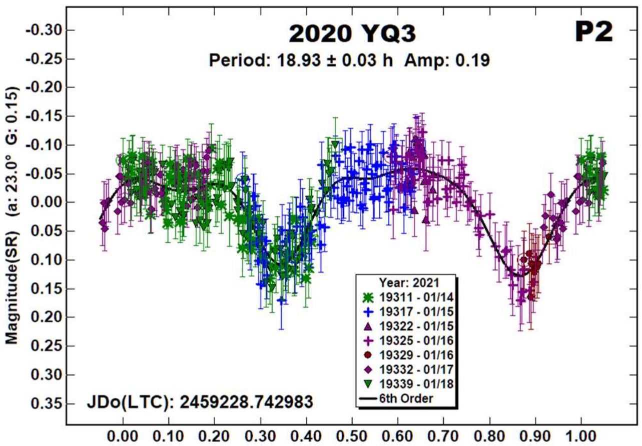


2020 YQ3. We observed 2020 YQ3 in 2021 from early to mid-January. The "NoSub" plot at a single period indicated that the asteroid was likely in a tumbling state.



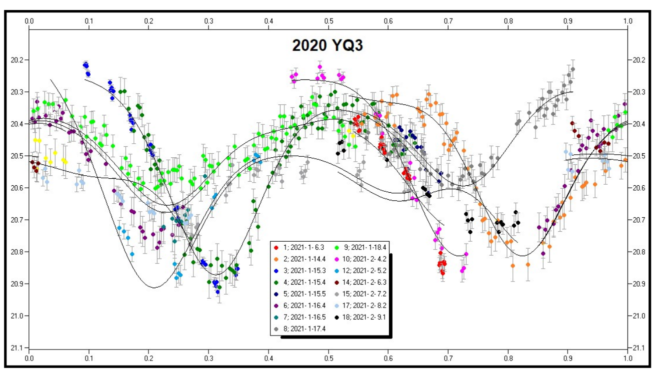
Even though *MPO Canopus* cannot properly handle tumbling asteroids, we tried the dual-period search feature since it seemed that there a was a strong dominant period in the data.



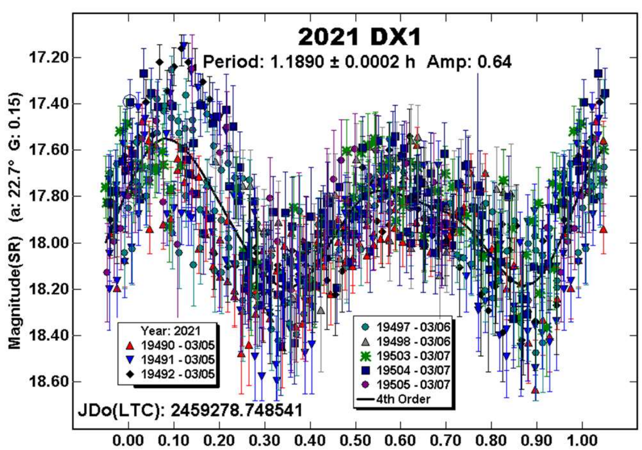


Our analysis led to P_1 = 11.148 h and P_2 = 18.93 h. Both produced good fits of the data to the Fourier curve. However, because of the limitations of the software, we forwarded our data to Petr Pravec, who incorporated our data with his obtained into mid-February. The combination of data from different longitudes and the proper software allowed him to find P_1 = 14.752 h and P_2 = 11.080 h (Pravec et al., 2021web), the latter being close to one of our periods.

Even his results should not be taken to be the definitive periods of precession and rotation. Their frequencies may be integral multiples of the ones derived here.



2021 DX1. Our data set led to a period of 1.189 h. However, there were signs of tumbling seen despite the noise.



We sent our data to Petr Pravec (private communications) who confirmed that the asteroid was tumbling and that one probable period was 1.19 h. He was observing the asteroid at that time and hoped to find a more definitive result after analysis of his data.

Acknowledgements

Thanks to Petr Pravec, Ondrejov Observatory, Ondrejov, CZECH REPUBLIC, for his advice and reviewing our data of suspected tumbling asteroids. Funding for observations at CS3 and work on the asteroid lightcurve database (Warner et al., 2009) and ALCDEF database (*alcdef.org*) are supported by NASA grant 80NSSC18K0851. The authors gratefully acknowledge Shoemaker NEO Grants from the Planetary Society (2007, 2013). These were used to purchase some of the telescopes and CCD cameras used in this research.

This work includes data from the Asteroid Terrestrial-impact Last Alert System (ATLAS) project. ATLAS is primarily funded to search for near earth asteroids through NASA grants NN12AR55G, 80NSSC18K0284, and 80NSSC18K1575; byproducts of the NEO search include images and catalogs from the survey area. The ATLAS science products have been made possible through the contributions of the University of Hawaii Institute for Astronomy, the Queen's University Belfast, the Space Telescope Science Institute, and the South African Astronomical Observatory.

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References from web sites should be considered transitory, unless from an agency with a long lifetime expectancy. Sites run by private individuals, even if on an institutional web site, do not necessarily fall into this category.

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Number	Name	2021 mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.
5879	Almeria	02/05-02/24	*33.7,30.0	164	8	21.967	0.003	0.17	0.02
65717	1993 BX3	02/22-03/05	13.5,4.0	160	-5	20.33	0.01	0.88	0.03
99942	Apophis	03/18-03/31	42.9,60.7	153	-8	30.62	0.01	1.06	0.05
162186	1999 OP3	01/12-01/15	11.6,9.9	128	6	8.36	0.03	0.04	0.01
164201	2004 EC	02/25-03/03	55.5,47.1	198	38	3.909	0.003	0.09	0.02
206359	2003 QM47	02/18-03/10	10.5,26.4	142	2	45.8	0.1	0.60	0.05
216707	2004 XP164	01/15-02/17	*20.9,13.9	138	5	15.517	0.004	0.37	0.06
		01/15-01/18	20.9,19.1	137	0	15.52	0.03	0.38	0.04
		02/05-02/17	8.7,13.9	139	0	15.483	0.007	0.32	0.03
332446	2008 AF4	01/09-01/11	65.5,49.8	139	7	3.0472	0.0006	0.14	0.02
		01/09	65.5	143	4	3.082	0.015	0.20	0.01
		01/10	56.7	140	6	3.041	0.005	0.14	0.01
		01/11	49.8	136	8	3.072	0.006	0.14	0.01
380359	2002 TN30	03/06-03/14	25.3,23.6	160	23	13.44	0.02	0.31	0.03
415029	2011 UL21	01/16-01/18	33.2,35.7	82	-5	3.31	0.01	0.05	0.02
438902	2009 WF104	01/06-01/18	20.6,29.2	116	21	175	20	0.52	0.10
	2003 YM1	01/15-01/18	12.9,12.2	126	-6	3.563	0.002	0.30	0.03
	2003 AF23	21/01/08-01/11	11.1,20.0	108	-8	^{T}20.1	0.1	0.77	0.05
						13.01	0.01	0.34	0.10
	2004 QD3	02/17-03/03	60.4,22.0	178	11	13.58	0.01	0.23	0.05
	2008 BC22	03/18-03/24	6.2,10.9	174	-2	40.4	0.3	0.25	0.05
	2015 AS45	02/05-02/11	38.1,39.2	170	4	47.9	0.2	0.22	0.03
	2018 PP10	02/17-02/20	8.1,2.6	150	3	6.91	0.01	0.07	0.02
	2020 WM3	02/05-02/17	*24.0,25.4	155	-14	11.60	0.02	0.21	0.03
	2020 YQ3	01/14-01/18	23.1,16.8	128	7	^{T}11.148	0.004	0.49	0.03
						18.93	0.03	0.19	0.02
Pravec	2020 YQ3	01/06-02/09	*41.4,13.0	130	6	^{T}14.752	0.003	0.65	0.05
Pravec et al. (2021web)						11.080	0.002		
	2021 DX1	03/05-03/07	22.7,20.2	177	2	^{T}1.1890	0.0002	0.64	0.10

Table III. Observing circumstances and analysis results. ^{T} Tumbling asteroid. The phase angle (α) is given at the start and end of each date range. If there is an asterisk before the first phase value, the phase angle reached a maximum or minimum during the period. L_{PAB} and B_{PAB} are, respectively the average phase angle bisector longitude and latitude (see Harris et al.,1984).

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